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TEMPERING EFFECTS FOR LOWER BAINITE, MARTENSITE, AND MIXED MICROSTRUCTURES ON IMPACT, FRACTURE, AND RELATED MECHANICAL PROPERTIES OF ASTM A723 STEEL

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Mixed microstructures were produced by cooling ASTM A723 steel from 830°C (1526°F) to lower temperatures, notably at 210° and 250°C (410° and 482°F), which are below the start of the martensite transformation (M_s) temperature of 286°C (547°F), and held for 2-1/4 hours. This resulted in the isothermal formation of 25 or 66 percent lower bainite as one part of the mixed microstructure with martensite. Tempering studies were conducted from 260° to 704°C (500° to 1300°F). Optimum tempering occurred at 593°C (1100°F), where differences between strength and hardness levels were minimized and the yield strength-to-ultimate tensile strength ratio was maximized. This allowed impact and toughness tests to be performed on an equal basis.

Impact tests, conducted from -100° to 88°C (-148° to 190°F), revealed that mixed microstructures could produce higher impact energy values compared to all-martensite. When the mixed microstructure containing 25 percent lower bainite was tested at -40°C (-40°F), the impact energy was increased by about 18 ft-lbs, compared to quenched and tempered martensite, and had the lowest ductile-brittle transition temperature of -73.3°C (-100°F) versus -68.3°C (-91°F) for martensite. Fracture toughness tests at -40°C revealed only a slight improvement in toughness for mixed microstructures at 188 Ksi√in., compared to all-martensite at 183.8 Ksi√in.

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INTRODUCTION

The steel currently used in the manufacture of modern large caliber cannon, as well as for many other high pressure applications, is a high strength, low alloy steel that follows ASTM A723. Historically, it has been thought that the optimum strength and toughness of this class of steel is obtained with a quenched and tempered martensite microstructure. When inferior properties occurred in this class of steels, one of the reasons usually cited was the presence of substantial amounts of bainite and martensite, indicating that an improper quench was applied to the steel. More recently, composite microstructures, consisting of tempered martensite and lower bainite formed by isothermal transformation below the start of the martensite transformation (M_S) temperature have shown promise, and, in this study, exceeded some of the properties of an all-martensite microstructure.

An increase in the properties of high strength, low alloy steels can normally be obtained by refining the microstructure. Refining the grain size increases strength, such as in the familiar Hall-Petch relationship, in which strength is shown to be inversely proportional to the grain size to the one-half power. Improvement in impact toughness and ductility is due to the refinement in the martensite microstructure by introducing lower bainite. In an earlier study, Hehemann (ref 1) suggested that lower bainite is formed when supercooled untransformed austenite is isothermally treated below the M_S temperature. He found that mechanical properties and toughness were superior or, in certain cases, equal to that of quenched and tempered martensite. He also found that properties improved as the temperature of isothermal transformation to lower bainite was decreased further below the M_S temperature. High temperature,

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relatively soft bainite formed much above the M_s temperature was detrimental to properties.

The objective of this study was to investigate the effect of mixed microstructures consisting of isothermally formed lower bainite and martensite versus conventionally quenched and tempered martensite to improve toughness.

EXPERIMENTAL PROCEDURE

The Mettler apparatus described by Cote (ref 2) was used to understand the isothermal transformation characteristics of A723 steel in obtaining a mixture of lower bainite and martensite. The apparatus combines differential thermal analysis (DTA) with a thermomagnetic analyzer. The output is a graph in which a peak indicates when a temperature difference occurs between a reference (standard) and a sample undergoing a phase transition. A magnetic force change, which usually accompanies the phase change, can also be recorded. The relative amounts of bainite and martensite were estimated by quantitative analysis using these DTA curves. The Mettler samples were heated to the austenitizing temperature (typically 830°C (1526°F)), then cooled at a minimum rate of 10°C (50°F) per minute to the desired transformation temperature below the M_s temperature, and held for 2½ hours before further cooling to room temperature. Bainite forms by a nucleation and growth process and requires time to complete the transformation, whereas martensite forms by a shear mechanism when the steel is continuously cooled with falling temperatures below the M_s temperature.

Using the above information, heat treatments were performed on A723 steel bars 5/8 inch square by 4½ inches long, which allowed mixtures of martensite and bainite to be formed, including lower bainite or martensite microstructures. Two muffle furnaces were connected to heat treat the bars. The rapid heating furnace with an alumina tube heated the separated bars placed within a double

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"D"-shaped crucible or boat to their austenitizing temperature of 830°C and held for one hour. Then the boat was moved into the split-type furnace with a mullite tube having good thermal shock resistance that allowed transformations to occur. The furnace, when partially opened, allowed forced air cooling to extract heat from the furnace and reduced the temperature to the proper transformation settings. At this point, the furnace was closed. Helium was used to reduce oxidation of the bars. All of the bars were held for 2½ hours at designated temperatures and then removed and rapidly air cooled to room temperature. Transformations took place at 210°C (410°F), 250°C (482°F), 300°C (572°F), and room temperature. This allowed formations of martensite with either 25 or 66 percent lower bainite, including all-bainite or all-martensite to be formed at the above temperatures, respectively. The M_s temperature was 286°C (547°F) for the A723 steel, for which the composition is shown in Table I. Bars obtained from the above treatments were tempered for one hour at temperatures from 260° to 704°C (500° to 1300°F) to arrive at an optimum tempering temperature. Heat treated bars were machined into 0.357-inch diameter smooth tensile specimens for tensile testing or standard V-notched Charpy bars for impact and fracture toughness testing. All tensile tests were performed at room temperature. Impact testing was conducted at temperatures in the -100° to 88°C (-148° to 190°F) range using heated water, refrigerated ethanol, and ethanol with liquid nitrogen for temperatures below about -50°C (-58°F). Some V-notched Charpy bars were precracked using fatigue cycling at low amplitudes of stress. These specimens were then used in three-point slow-bend tests at -40°C (-40°F) to provide fracture toughness values. Fractographs were obtained using the scanning electron microscope (SEM), and photomicrographs were taken from polished and etched end pieces in the longitudinal direction of the forging.

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The etching solution consisted of 2 percent picric acid in alcohol, to which seven drops of hydrochloric acid were added per 100 ml of solution.

RESULTS

Heat Treat Response

Isothermal transformation studies revealed that mixtures of lower bainite and martensite could be produced with 25 or 66 percent bainite by isothermal transformation at 210° and 250°C, respectively, after cooling from an austenization temperature of 830°C. These transformations occurred below the M_s temperature of 286°C. The microstructure, consisting completely of isothermal lower bainite, was produced by holding the specimens at 300°C for the 2¼-hour transformation time period. This same holding time was used to transform austenite to mixed microstructures before cooling to room temperature.

To evaluate impact and fracture toughness testing on an equal basis, tempering was performed so that hardness, yield strength, and, to some extent tensile strength, were as equal as possible. This was done by selecting the correct tempering temperature for all the microstructures. A profile of hardness values after tempering at 260° to 704°C is shown in Figure 1. A crossover of the mixed microstructure with martensite or lower bainite occurred at 593°C (1100°F). The mechanical properties for each category of materials tested are shown in Table II. These properties provided the necessary data to evaluate the effect of tempering in the 260° to 704°C temperature range. The ratio of yield strength-to-ultimate tensile strength, when plotted as a function of tempering temperature, is shown in Figure 2. The maximum yield strength-to-ultimate tensile strength occurred for all microstructures at 593°C. When these ratios were plotted against ultimate tensile strength values, as shown in Figure 3, a general convergence of the plots was observed. Each plot represents a

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particular microstructure with a maximum ratio of about 0.95 and an ultimate tensile strength value of approximately 170 Ksi (1172 MPa) obtained by tempering at 593°C. The curve representing isothermal lower bainite, however, fell below the yield strength-to-ultimate tensile strength ratio attained by the other microstructures, as seen in Figures 2 and 3. Yield strength decreased as the percent of lower bainite was increased for most of the tempering temperatures used, as shown in Figure 4. The exception was at 593°C, where strength values were maintained and only started to decline as lower bainite amounts exceeded about 66 percent. Ultimate tensile strength behaved in much the same manner, as shown in Figure 5.

Microstructural Response to Heat Treatments

The response of the composite microstructure containing 66 percent lower bainite and martensite to tempering is shown in Figure 6. After being austenitized at 830°C, the samples were cooled to 250°C and held for 2¼ hours. They were then tempered, after cooling to room temperature, at the temperatures indicated in the figure for one hour. These microstructures do not show a marked change after tempering, except at the highest temperature used. The microstructure for the 704°C temper appeared to be in the early stage of spheroidization and was different from the other ones. A drastic drop in the yield strength-to-ultimate tensile strength ratio was also noted for the 704°C temper for all the microstructures. A comparison of microstructures in the untempered condition is shown in Figure 7. Only untempered martensite appeared different from the mixed microstructures, including bainite, when tempered at 593°C. A difference in the metallographic appearance, a result of increased amounts of lower bainite in the microstructures, was desired as a way to compare the amounts in Figure 8 with those from DTA analysis. Increasing amounts of isothermal lower bainite were

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undetectable from metallographic observations of the etched microstructures shown in Figure 8. New etching techniques (ref 3) were developed, but they were not used in this study. Figure 8 indicates the effect of using a higher austenitizing temperature of 930°C (1706°F) rather than 830°C. It appears that the microstructures (untempered), which do not show much of a difference because of the amount of bainite transformed, do show a coarsening effect due to the higher austenitizing temperature of 930°C. The coarsening effect is in conjunction with grain growth emphasized when a grain boundary etch was used, revealing the prior austenite grain size that grew significantly, as shown in Figure 9.

Fracture Toughness

When the higher austenitizing temperature was used in a previously unpublished pilot study*, fracture toughness values for mixed microstructures were reduced from about 188 Ksi$\sqrt{\text{in}}$. to 110 Ksi$\sqrt{\text{in}}$., as shown in Table II. Most likely, the values decreased due to the increased grain size and a larger packet** size containing laths of lower bainite and martensite transformed from austenite. The fracture toughness of bainite was reduced from about 200 to 80 Ksi$\sqrt{\text{in}}$., while for martensite, a much less drastic reduction from 184 to 155 Ksi$\sqrt{\text{in}}$. occurred. The above corresponding lower values (for which the data are not included in this report) are mentioned here in conjunction with the fractographs shown in Figures 10 and 11. Figure 10 shows the fracture patterns obtained from fracture toughness specimens tested in three-point bending at -40°C with increases in lower bainite. The 100 percent martensite fracture revealed that a ductile fracture occurred by microvoid coalescence, and in the 100 percent bainite fracture, a quasi-cleavage pattern was evident. A very

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*Conducted in the Materials Engineering Branch of Benet Laboratories in 1988.
**A packet is defined as a group of parallel laths as compared to that obtained with single-phase martensite.

ductile fracture occurred for the microstructure containing 66 percent bainite (transformed at 250°C) indicating that serpentine glide, together with micro-void coalescence, took place. When the higher austenitizing temperature was used to obtain the same percentages of lower bainite transformed at the same temperatures, lower fracture toughness values were revealed and reflected in the fractures, as shown in Figure 11. Except for martensite, which still failed in a ductile manner, the predominant fracture mode was cleavage. As a result, less than half the fracture toughness values were obtained at 930°C than at 830°C.

The effect of tempering on fracture surfaces of microstructures containing martensite with 25 and 66 percent of lower isothermal bainite is shown in Figure 12. As indicated in Table II, fracture toughness values using the 593°C temper increased from 183.8 Ksi$\sqrt{in}$. for martensite to 201.4 Ksi$\sqrt{in}$. for bainite. The mixed microstructures with 25 and 66 percent lower bainite had almost equal values of 187.5 and 188 Ksi$\sqrt{in}$., respectively. These high fracture toughness values, which peaked when tempered at 593°C, are reflected in their fracture patterns.

The fractures in Figure 12 reveal that very ductile yielding by a serpentine glide mechanism occurred in both mixed microstructures when the 593°C temper was used, while a quasi-cleavage mode of failure indicating lower energy absorption was seen with tempers up to this temperature. Tempering at 704°C resulted in a sharp decline in values for both mixed microstructures. Although the fracture patterns appear somewhat similar, the decline in fracture toughness was more pronounced with 25 percent than with 66 percent lower bainite.

Impact Testing

Impact tests were conducted over a temperature range of -100° to 88°C. The average impact values for all microstructures tested are shown in Table III.

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The resulting impact values are shown as a function of temperature in Figures 13 and 14. Impact values for the mixed microstructure with 66 percent lower bainite closely followed the values recorded for all-martensite from very low temperatures to about -51.1°C (-60°F). Above this temperature, the mixed microstructure is clearly superior. The microstructure containing 25 percent lower bainite generally produced the highest impact values, as shown in Figure 13. The untempered bainite microstructure produced the lowest impact values compared to all the others tested. Impact values for tempered bainite improved above -17.8°C (0°F) compared to martensite, with upper shelf energy values closely following recorded values for the mixed microstructures up to 88°C, as shown in Figure 14. Upper shelf energies with 25, 66, and 100 percent bainite microstructures were about 20 ft-lbs higher than for martensite above 0°C (32°F).

The ductile-brittle transition temperatures (DBTT) for all microstructures are shown in Table IV. The highest transition temperature of 1.1°C (34°F) was recorded for untempered bainite, while the lowest transition temperature of -73.3°C (-100°F) was recorded for the mixed microstructure with 25 percent lower bainite. The second lowest transition temperature recorded was for martensite at -68.3°C (-91°F). A comparison of impact fracture surfaces at -40° and -70°C (-94°F) is shown in Figure 15. The fractures from impact tests at -40°C reveal that the mixed microstructure containing 25 percent lower bainite had a very ductile fracture pattern with tearing or serpentine glide present and produced the highest impact value of 67.3 ft-lbs. The fracture surface for 66 percent lower bainite reveals some areas of quasi-cleavage and microvoid coalescence, which was seen predominantly for martensite at this same temperature. Cleavage and quasi-cleavage fractures were dominant when testing was done at -70°C, as

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shown in Figure 15. Quasi-cleavage facets were much smaller for the microstructure containing 25 percent lower bainite, indicating higher energy absorbed prior to failure at -70°C. Fractures for the tempered bainite microstructure consisted of large cleavage facets when tested at the above temperatures, which were below the DBTT of -12.8°C (9°F), as indicated in Table IV.

DISCUSSION

Hehemann (ref 1) was one of the first to study the properties of mixed microstructures consisting of lower bainite and martensite, as influenced by the amount of bainite, the reaction temperatures of formation, and the strength levels of the aggregate. He found that for a fixed tempering temperature, mixed microstructures exhibited lower tensile strengths than an all-martensite microstructure in aircraft quality 4340 steel. This same trend was found in the present study for tempering temperatures below 593°C. However, when 593°C was used, tensile and most yield strengths were approximately the same for all the microstructures studied, except for 100 percent lower bainite. This behavior is shown in Figures 4 and 5. Tensile ductility, as measured by reduction-in-area, was a complex function of strength level and the formation temperature of bainite. Bainite formed at high temperatures much above the M_S temperature generally reduced ductility at all strength levels, while damage to ductility became less severe as the reaction temperatures were lowered. It is generally believed that the damaging influence on the ductility of high temperature bainite primarily resulted from the reduction in strength of bainite as the reaction temperatures were raised. Hehemann believed that the relative hardness difference of microconstituents in a mixed microstructure was the primary cause of the loss of ductility regardless of the microstructure involved. However,

since hardness is a manifestation of many metallurgical factors, one of which is microstructure, the two forms of bainite should be examined more closely.

Upper bainite forms at relatively high temperatures just below the range of pearlite formation with lower hardness values than lower bainite and martensite. Upper bainite forms in patches or blocks containing many parallel laths of ferrite. Carbon is rejected from the ferrite and concentrates to form relatively coarse cementite (carbide) particles as dark stringers between ferrite laths. The nature of this formation indicates planes of weakness along these carbide stringers. Lower bainite, which forms at much lower temperatures than upper bainite, develops a plate-like morphology and carbides appear as very fine particles within the ferrite plates that are not usually distinguishable when viewed in the light microscope. Lower bainite forms at angles to each other giving the microstructure an acicular or needle-like appearance much like martensite. Upper bainite was not used in the present study of mixed microstructures, therefore, ductility was not impaired during isothermal transformation to lower bainite. A close match of tensile properties and hardness values was attained when an optimum tempering temperature of 593°C was used. This temperature, which allowed maximum yield strength-to-ultimate tensile strength ratios for all microstructures to be attained (as shown in Table II), enabled a fair evaluation of toughness for the microstructures tested.

The elimination of retained austenite is usually desirable in steel processing, since austenite may later transform to untempered martensite and degrade properties. Partial transformation of austenite to bainite increases the amount of austenite retained at room temperature (refs 4,5). The tendency for austenite retention and carbon enrichment in austenite is intimately connected with the reaction temperature imposed, the alloy content of the type of

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carbide that precipitates, and the rate of precipitation from ferrite or austenite, as in the case of upper bainite. For sufficiently long reaction times, the lower the reaction temperature, the smaller the amount of retained austenite. Austenite was not observed in the microstructures examined, and although x-ray analysis was not used, it seems unlikely that it was retained in appreciable amounts. This is assumed, since all the reaction temperatures were kept below the M_S temperature and held for sufficiently long times, as previously determined by DTA studies for complete transformation to lower bainite. Reduction-in-area values were not impaired and were greater for the mixed microstructures than for martensite. The dramatic reduction in the amount of retained austenite associated with the formation of lower bainite is particularly significant and emphasizes the fundamental difference between upper and lower bainite.

The properties arrived at by using a comparatively low strength second phase, such as bainite, mixed with higher strength martensite in similar high strength steels were studied by Tomita and Okabayashi (refs 6-8). They found that the mechanical properties of such mixed microstructures were significantly affected by the size, shape, and distribution of the bainite second phase and not by the difference in hardness or strength between the two phases. The effectiveness of isothermal treatments on AISI 4340 steel to improve some mechanical properties was because lower bainite effectively caused a refinement of the lath width and packet size of the parent martensite. This led to a tougher material with strength values equal to or greater than martensite. Other investigators (refs 9-16) also have shown that an increase in toughness of high strength steels can be obtained by decreasing the lath width and packet size of the martensite in addition to reducing the grain size. Tomita and Okabayashi found that when isothermal lower bainite appeared in acicular form

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with martensite, it partitioned the prior austenite grains of the parent marten-
site. This is shown schematically in the Appendix. Lower bainite provided
increased resistance to brittle fracture at low temperatures. The yield
strength attained by mixed microstructures followed a rule of mixtures with some
revised data gathered using smooth tensile bars. Compensations were needed for
the increased strength of martensite due to refinement of its microstructure,
and, in some instances, for the increased strength of lower bainite due to the
plastic restraining by martensite when tempered at low temperatures. The 0.2
percent proof or yield strength of a mixture of bainite and martensite is given
by the simple rule of mixtures in Eq. (1)

$$\sigma_{0.2}^{Mix} = \sigma_{0.2}^{M}(1-V_B) + \sigma_{0.2}^{B}(V_B) \tag{1}$$

Revising Eq. (1) resulted in the following revised rule of mixtures:

$$\sigma_{0.2}^{Mix} = (\sigma_i + KS_M^{-\frac{1}{2}})(1-V_B) + \sigma_{0.2}^{B}(V_B) \tag{2}$$

Equation (2) was based on the premise that in the mixed structure the martensite
size S_M, when partitioned by lower bainite, is narrowed and decreases as the
volume fraction of bainite V_B increases. This, in turn, causes a refinement of
the packet size that contributes greatly to the improvement in the yield
strength of the mixture. It was necessary to account for the strengthening of
martensite according to the Hall-Petch relationship given as $\sigma_{0.2}^{M} = \sigma_i + KS_M^{-\frac{1}{2}}$,
where $\sigma_{0.2}^{M}$ is the 0.2 percent yield strength of martensite in the mixed
microstructure. σ_i and K are approximated by the intercept and slope arrived
at when the 0.2 percent yield strength of martensite versus the reciprocal
square root of the austenite grain size is plotted for each of the tempering
temperatures martensite has undergone, as shown in the Appendix. Substitution
of the expression $\sigma_{0.2}^{M}$ into Eq. (1) resulted in Eq. (2) and in another form
shown as Eq. (3) in the Appendix. If enhanced strengthening of bainite results

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from much higher plastic restraining by the parent martensite in the early sta-

ges of deformation. It consequently causes $\sigma^B_{0.2}$ to reach $\sigma^M_{0.2}$. Therefore,

$\sigma^{Mix}_{0.2} = \sigma_i + KS_M^{-\frac{1}{2}}$, as stated by Eq. (4) in the Appendix. Tomita and Okabayashi

(ref 8) found that when lower bainite was associated with martensite tempered at

200°C (392°F), experimental data agreed with Eq. (4) up to 25 volume percent,

but beyond this amount of bainite, Eq. (2) was followed. When the difference in

the strength between bainite and martensite became small because of higher tem-

pering temperatures of 400° and 600°C (932° and 1112°F), their data exhibited

much better agreement with Eq. (2), regardless of the volume fraction of lower

bainite.

The yield strengths developed from this study, plotted as a function of

volume percent of lower bainite, are shown in Figure 4. The data indicate that

strength generally decreases as the percent of bainite increases. This is

equally true for the ultimate tensile strength shown in Figure 5. The exception

was for mixed microstructures tempered at 593°C, where strength levels were

maintained for mixtures up to about 66 volume percent lower bainite. Beyond

this, strength values decreased to the values obtained for 100 volume percent

bainite. The simple and revised rules of mixtures were used to calculate yield

strengths to compare with actual test results. Mixtures containing 25 volume

percent bainite tempered at 371°C (700°F), 482°C (900°F), and 593°C had calcu-

lated values averaging 1.16 percent lower than the actual values using Eq. (1).

When Eq. (2) was used, the average calculated values were about 5.58 percent

lower than the actual values attained. Yield strengths for a mixed microstruc-

ture containing 66 volume percent bainite and the same tempering temperature had

calculated values 2.49 percent higher for the 371°C temper and 7.4 percent lower

for the 482° and 593°C tempers using Eq. (1). When Eq. (2) was used, the

calculated values for the above tempering temperatures were 1.90, 9.25, and 16.3 percent lower, respectively, than those actually attained. The yield strength resulting from the 260°C temper for both the simple and revised rules of mixtures had predicted values 10 and 15 percent higher, respectively, for a mixture with 25 percent bainite and 15.4 and 24.9 percent higher, respectively, for a mixture with 66 percent bainite. Predicted yield strengths for the 260°C temper were much higher than actually attained using either equation. This may be partly due to the very large disparity between the yield strength and the ultimate tensile strength caused by tempering within the 260°C embrittlement range for this steel. Equation (1) best fits the data in this study for the yield strengths attained, especially for a mixture containir 25 percent bainite. This may be because when using Eq. (2), the Hall-Petch parameters taken from References 6 and 7 were inaccurate, since the tempering temperatures did not coincide with this study. The one exception was approximated by the 593°C temper. Also, yield strengths in this study were taken at the 0.1 percent offset rather than the 0.2 percent offset. Another source of discrepancy was that the steel contained 0.10 weight percent vanadium, whereas the AISI 4340 steel did not (ref 6).

Compared to martensite, the improved impact values found in this study by using mixed microstructures were higher, both at lower and higher temperatures, as shown in Figures 13 and 14. An increase in impact values of about 18 to 20 ft-lbs is evident for the mixed microstructure with 25 percent bainite compared to martensite for test temperatures in the -51.1° to 88°C range. This mixture produced the lowest DBTT of -73.3°C, resulting in a -12.8°C reduction in the transition temperature. Transition temperatures were progressively lower as the temperature for isothermal bainite formation was reduced below 286°C, as shown in Table IV. The all-bainite tempered microstructure showed improvement equal

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to that of the mixed microstructures only above -17.8°C with an upper shelf
energy near 76 ft-lbs. while untempered bainite only reached a value of 50 ft-
lbs at 88°C.

Nakajima and Araki (ref 17) studied two medium carbon steels with 1.80 per-
cent nickel in the AISI 43XX-type steels. They varied the content from 1.41
manganese for the 0.34 carbon steel to 0.86 manganese for the 0.54 carbon steel.
The higher manganese content was used to retard the bainite formation and the
embrittlement of martensite when tempered at temperatures normally in the
embrittlement range to match the hardness of as-transformed bainite. Exact com-
parisons with A723 steel cannot be made; however, general conclusions apply to
the current study since the lower the isothermal transformation temperature used
to form bainite. the lower the impact transition temperature for the same hard-
ness level. Also. the transition temperature of a mixed microstructure of mar-
tensite and bainite formed below the M_S temperature was lower than for bainite
formed above the M_S temperature. and the transition temperature of martensite
was generally lower than for bainite--the difference depending on tempering con-
ditions.

Another of Nakajima and Araki's findings was that the transition tem-
perature dropped inversely as the minus one-half power of the fracture facet
size at the same hardness levels. The transition temperature depended on the
amount and the manner that carbides precipitate in producing fractures. The
microstructures with bainite had higher impact energy values with smaller
cleavage facets. The carbides in bainite normally precipitate within the laths.
On the other hand. in the martensite microstructures, carbides precipitate within
the lath and also on the lath boundaries. These carbides usually agglomerate
progressively as tempering temperatures are raised. Their presence facilitates

formation of cleavage cracks, especially after tempering and in unfavorable locations, such as on the lath or grain boundaries. Reduced toughness and an increase in transition temperature can be expected when these conditions exist.

Cleavage facet measurements were not completed for this study, however, the types of fracture features seen in Figure 15 follow the same trend: the smaller the facet size, the higher the impact values and the lower the transition temperature. Impact values of 36.6, 49.5, 33.4, and 24.5 ft-lbs were recorded at -70°C for microstructures with 100 percent martensite, 25 percent bainite, 66 percent bainite, and 100 percent bainite, respectively. The refinement in facet size is readily apparent for the fracture surface of the 25 percent bainite microstructure with the highest impact energy and the lowest transition temperature.

The more critical fracture parameter to consider is the propagation of an already existing crack. Nakajima and Araki (ref 17) found that a standard Charpy bar with a machined V-notch, consisting of a lower bainite microstructure, required higher impact energy to break the bar than a martensite microstructure at all testing temperatures. When a sharper notch, e.g., a crack, was introduced before testing, only a small difference in impact values between microstructures was recorded. They concluded that while bainite requires more energy to initiate a macroscopic crack than martensite, the energy to propagate an already existing crack in both was not much different. Also, the impact transition temperature was more correlated with crack initiation than with propagation of an already existing crack.

Another measure of toughness to consider in a material is fracture toughness, which uses a specimen containing a precrack induced by fatigue cycling. Fracture toughness of heat treated low alloy steels tempered at lower

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temperatures is thought to be controlled by the microstructural feature produced during the austenitizing cycle rather than later tempering schedules. Retained austenite content (refs 9,18,19), distribution of residual carbides from both iron and alloying elements (refs 20,21), prior austenite grain size (refs 10,12,21,22), and packet diameter (ref 23) are factors in fracture toughness testing.

Tomita (ref 24) suggested that low temperature improvement in the mechanical properties of quenched and tempered 4340 steel is controlled by the packet diameter rather than the prior austenite grain size, which was thought to be a dominant microstructural feature controlling fracture toughness values. Fractography studies revealed that in martensite and lower bainite steels, the quasi-cleavage facet size is in good agreement with the packet diameter and is believed to be the primary microstructural factor determining fracture toughness. Tomita found that a mixed microstructure with 25 percent lower bainite and martensite resulted in a higher fracture toughness than martensite and lower bainite with the same grain size (13.55 μm) when austenitized at 900°C (1652°F). However, when upper bainite was substituted for lower bainite in the mixed microstructure, the fracture toughness values were reduced by about thirty percent. The martensite microstructure had 20 percent lower fracture toughness values, compared to the mixed microstructure whose values were only slightly higher than 100 percent lower bainite. Tomita attributed the improved fracture toughness values for the mixed microstructure to the crack arrest effect by the second phase bainite and to the stress relief effect by the lower bainite ahead of the running crack. The appearance of a ductile phase, e.g., retained austenite, is not necessarily effective in improving fracture toughness values. However, for steel with a ductile second phase, fracture toughness is strongly

influenced by the shape and distribution of the second phase rather than volume fraction. This was emphasized by Tomita and Okabayashi (ref 8) when fracture toughness values were compared for microstructures containing either upper or lower bainite in the parent martensite. Lower bainite, which appears in acicular form, partitions prior austenite grains of the parent martensite and, as a ductile second phase, relieves stress concentrations at the crack tip that blunt it to provide a ductile fracture. This is because the second phase bainite can make full use of its toughness since the bainite deforms in association with the parent phase as a result of plastic restraining by the parent martensite. Thus, excessive loads are not applied to the second phase separately during deformation. When upper bainite in blocky form is associated with the tempered martensite in a mixed microstructure, the bainite meeting the crack tip (within the plastic zone) fractures in a brittle manner decreasing the fracture toughness values. This is because a much higher stress concentration is produced in the vicinity of the interface caused by a non-uniform strain that exists between the two phases during deformation.

In this study, the fracture toughness values shown in Table II for mixed microstructures with either 25 or 66 percent lower bainite were slightly higher than for an all-martensite microstructure. However, they were lower than 100 percent bainite, which was not the case in Reference 8. This could be due to a much lower yield strength exhibited by lower bainite with twice the difference between yield and tensile strength compared to all the other microstructures with the same tempering temperature of 593°C. This could override other favorable advantages attributed to mixed microstructures, since previously the results were compared on an equal strength basis. When austenitizing

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temperatures were raised from 830° to 930°C in a previously unpublished pilot study, fracture toughness values for all microstructures declined drastically, except for quenched and tempered martensite. Grain growth was appreciable, as shown in Figure 9. An unfavorable packet size with an unfavorable distribution and carbide size may have occurred in the microstructures containing lower bainite causing the decline in fracture toughness values when the higher austenitizing temperature was used.

SUMMARY

1. Tempering studies conducted on A723 steels from 260° to 704°C revealed that optimum tempering at 593°C was produced for mixed microstructures, lower isothermal bainite, and martensite. This resulted in the maximum yield strength-to-ultimate tensile strength ratios. The highest values of tensile ductility (reduction-in-area) and fracture toughness were also recorded.

Yield and ultimate tensile strengths for mixed microstructures declined rapidly when increasing amounts of lower bainite were added to martensite. Tempering over the above-mentioned range of temperatures also decreased strength values. The exception was at 593°C, where yield and ultimate tensile strength were independent of the amount of bainite until about 66 percent lower bainite, where a decline in strength levels began and continued until the lowest strength values were reached at 100 percent lower bainite.

2. Impact testing for mixed microstructures with 25 and 66 percent bainite generally produced higher energy values than all-bainite or all-martensite when tested at temperatures from -100° to 88°C. Impact values at -40°C were about 18 ft-lbs higher for a mixed microstructure containing 25 percent lower bainite than for martensite, with upper shelf energy values continuing this trend. This

microstructure produced the lowest DBTT of -73.3°C compared to martensite at -68.3°C. Lower tempered bainite with low impact values produced a DBTT of only -12.8°C.

3. Fracture toughness values recorded for mixed microstructures with 25 and 66 percent lower bainite in slow-bend tests at -40°C were only slightly higher at 188 Ksi$\sqrt{in}$. than martensite at 183.8 Ksi$\sqrt{in}$. and indicated that propagation of an existing crack was not much different in these microstructures. Lower bainite produced the highest value (201.4 Ksi$\sqrt{in}$.), but it had strength levels below the other microstructures and the disadvantage of low impact properties.

4. Austenitizing at 830°C prior to isothermal transformation to lower bainite produced the highest fracture toughness values and a small ASTM grain size number of 10.5. However, as discovered in a previously unpublished pilot study, using 930°C resulted in consistently low fracture toughness values (110 Ksi$\sqrt{in}$.) over most of the range of compositions with cleavage-type brittle fractures observed and produced a large ASTM grain size number of 7.3.

5. Evidence from this study revealed that mixed microstructures containing either 25 or 66 percent lower bainite produced by isothermal transformation below the M_s temperature can result in superior toughness as compared to quenched and tempered martensite when heat treated to the same normal yield and tensile strength levels usually intended for this steel.

The improvement in toughness, especially as found in impact studies, was more pronounced as the temperature of isothermal transformation was further lowered below the M_s temperature.

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TABLE I. COMPOSITION* OF ASTM A723 STEEL**
(M_s TEMPERATURE 286°C)

Copper	0.34
Manganese	0.62
Phosphorus	0.008
Sulfur	0.004
Silicon	0.16
Nickel	3.18
Chromium	1.02
Molybdenum	0.48
Vanadium	0.10
Aluminum, Titanium	0.005

*Weight Percent

**Process Steps

Melting Process: (Typical)	Electric furnace, vacuum degassed, electroslag remelt ingot.
Forging Reduction:	Ingot to forged diameter ratio 1.83/1.00, then rotary forged (15 percent bottom, 50 percent top) to near net final diameter.
Specimen Location:	Bars taken in radial (transverse) direction from bottom end of forging.

TABLE II. MECHANICAL PROPERTIES FOR A723 STEEL
(HEAT TREATMENTS INDICATED)

Temper °C (°F)	%RA	%El	0.1% YS (Ksi)	UTS (Ksi)	Rockwell Hardness (R_A)	0.1% YS UTS	K_{Ic} (Ksi$\sqrt{in}$.)
25% Bainite 830°C to 210°C, 2½ hrs							
No Temper	48.6	9.4	122.7	234.0	74.3	0.52	75.2
260 (500)	46.5	11.1	157.4	234.8	74.0	0.67	89.7
371 (700)	45.4	11.2	184.2	217.9	73.3	0.84	90.5
482 (900)	52.4	14.4	181.6	195.3	71.9	0.93	155.0
593 (1100)	58.7	15.5	162.3	170.8	69.3	0.95	187.5
704 (1300)	35.7	13.7	87.7	188.1	69.4	0.47	111.0
66% Bainite 830°C to 250°C, 2½ hrs							
No Temper	52.3	19.7	112.5	227.7	72.4	0.49	99.8
260 (500)	56.8	14.9	132.8	213.4	70.9	0.62	100.2
371 (700)	57.2	15.5	154.1	200.1	70.5	0.77	102.6
482 (900)	62.2	14.2	171.6	190.2	69.4	0.90	132.6
593 (1100)	59.7	13.3	162.5	175.6	68.2	0.93	188.0
704 (1300)	48.2	12.5	84.6	186.3	67.9	0.45	136.7
All-Bainite 830°C to 300°C, 2½ hrs							
No Temper	56.7	12.0	110.0	200.5	71.5	0.55	89.9
260 (500)	49.8	10.8	117.4	202.4	71.3	0.58	97.2
371 (700)	59.1	12.9	135.3	193.7	71.0	0.70	104.9
482 (900)	55.0	14.6	142.2	180.0	70.0	0.79	138.3
593 (1100)	57.7	16.3	144.1	163.9	68.2	0.88	201.4
704 (1300)	46.5	16.3	84.4	140.2	66.2	0.60	88.5

%RA: percent reduction-in-area; %El: percent elongation; YS: yield strength; UTS: ultimate tensile strength; K_{Ic}: fracture toughness

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TABLE II. CONTINUED

Temper °C (°F)	%RA	%El	0.1% YS (Ksi)	UTS (Ksi)	Hardness (R_A)	0.1% YS UTS	K_{IC} (Ksi$\sqrt{in.}$)
All-Martensite 830°C to Room Temperature							
No Temper	27.0	8.5	166.2	280.9	76.2	0.59	63.8
260 (500)	42.8	10.7	202.5	254.2	75.2	0.80	96.4
371 (700)	43.6	9.3	201.9	230.4	73.5	0.88	111.5
482 (900)	45.5	11.0	191.3	205.4	71.9	0.93	151.4
593 (1100)	51.8	13.9	162.7	173.2	69.4	0.94	183.8
704 (1300)	31.3	12.6	82.9	172.8	68.4	0.48	142.3

TABLE III. AVERAGE CHARPY IMPACT VALUES* FOR A723 STEEL TEMPERED AT 593°C AND UNTEMPERED

Temperature °C (°F)	All-Martensite	25% Bainite	66% Bainite	All-Bainite	Untempered Bainite
88 (190)	56.75 (76.94)	76.80 (104.13)	77.25 (104.74)	76.25 (103.38)	70.00 (94.91)
60 (140)	56.50 (76.60)	75.70 (102.63)	71.50 (96.94)	75.50 (102.36)	49.33 (66.88)
22.2 (72)	54.17 (73.44)	74.00 (100.33)	71.38 (96.78)	73.10 (99.11)	42.60 (57.76)
0 (32)	53.50 (72.54)	69.65 (94.43)	67.50 (91.52)	69.67 (94.46)	30.33 (41.12)
-17.8 (0)	50.00 (67.79)	68.00 (92.19)	70.50 (95.58)	51.75 (70.16)	25.00 (33.90)
-40 (-40)	49.15 (66.64)	67.30 (91.24)	56.00 (75.92)	34.67 (47.00)	20.83 (28.24)
-51.1 (-60)	45.90 (62.23)	64.50 (87.45)	48.50 (65.76)	30.16 (40.89)	17.25 (23.39)
-70 (-94)	36.63 (49.66)	49.50 (67.11)	33.40 (45.28)	24.50 (33.22)	14.00 (18.98)
-78.9 (-110)	28.75 (38.98)	42.00 (56.94)	27.50 (37.28)	22.33 (30.28)	13.75 (18.64)
-90 (-130)	22.55 (30.57)	26.40 (35.79)	26.50 (35.93)	20.50 (27.79)	13.67 (18.53)
-100 (-148)	18.73 (25.39)	20.16 (27.33)	26.25 (35.59)	19.33 (26.21)	13.25 (17.96)

*ft-lbs (joules)

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TABLE IV. CHARPY V-NOTCHED TRANSITION TEMPERATURES FOR
A723 STEEL TEMPERED AT 593°C

| Treatment | Microstructure | DBTT* | |
		°C	°F
836° to 300°C, 2¼ hrs	bainite (untempered)	1.1	34.0
836° to 300°C, 2¼ hrs	all-bainite	-12.8	9.0
836° to 250°C, 2¼ hrs	mixed, 66% bainite	-50.0	-58.0
836°C to room temperature	all-martensite	-68.3	-91.0
836° to 210°C, 2¼ hrs	mixed, 25% bainite	-73.3	-100.0

*Graphical determination used for the ductile-brittle transition
temperatures
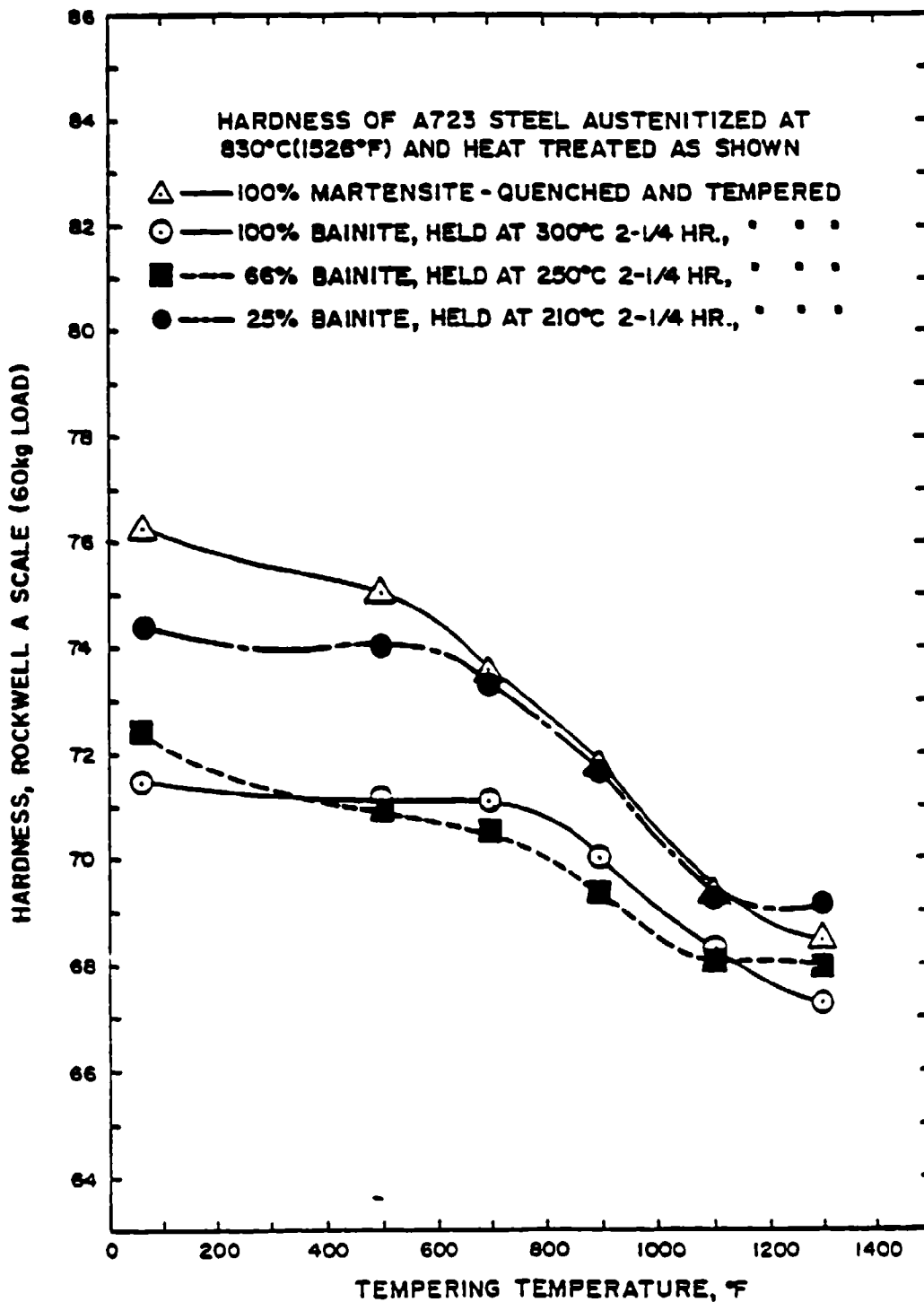
Figure 1. Hardness of A723 steel austenitized at 830°C and tempered from 260° to 704°C.
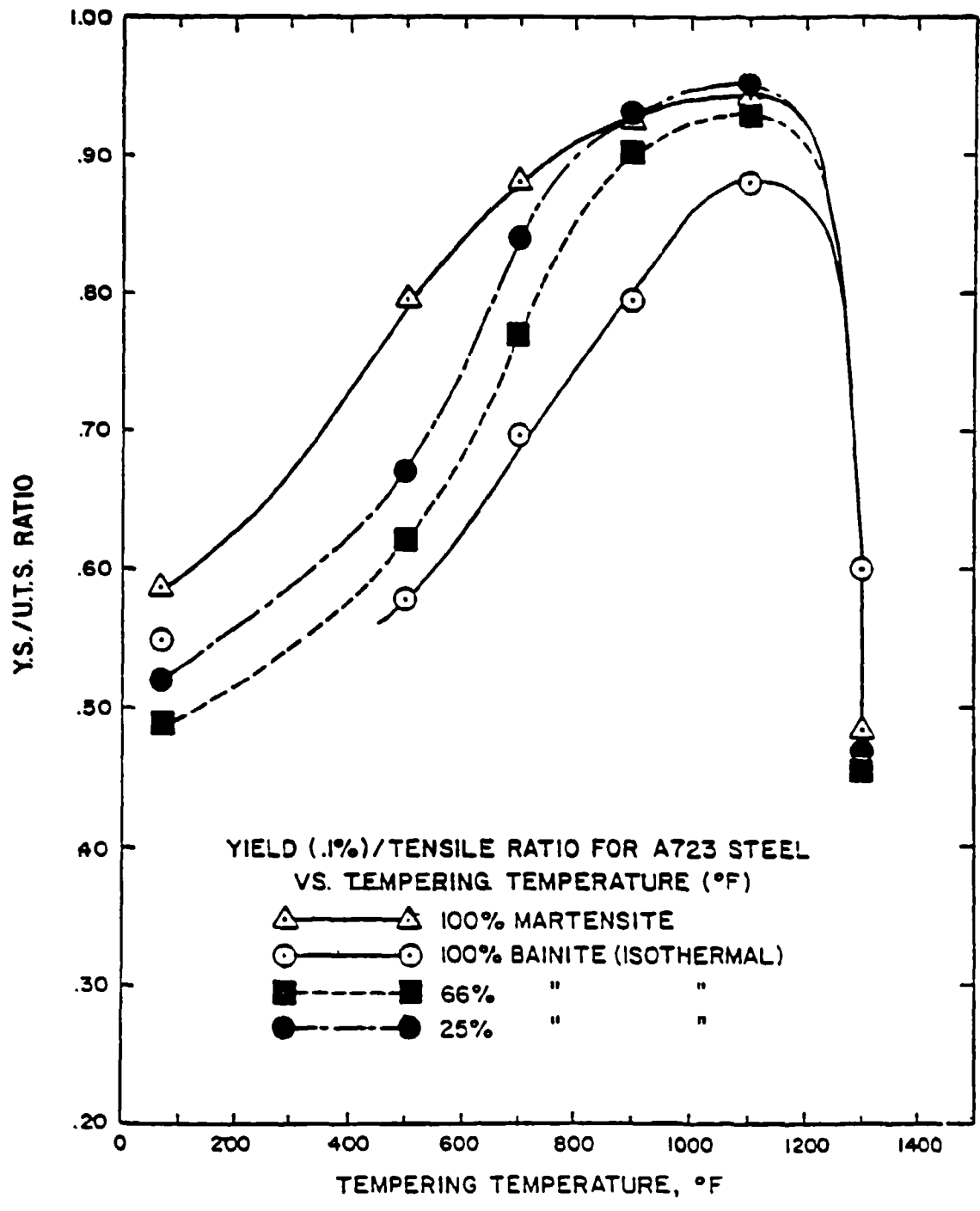
Figure 2. The effect of microstructure on the yield strength-to-ultimate tensile strength ratio as a function of tempering temperatures.

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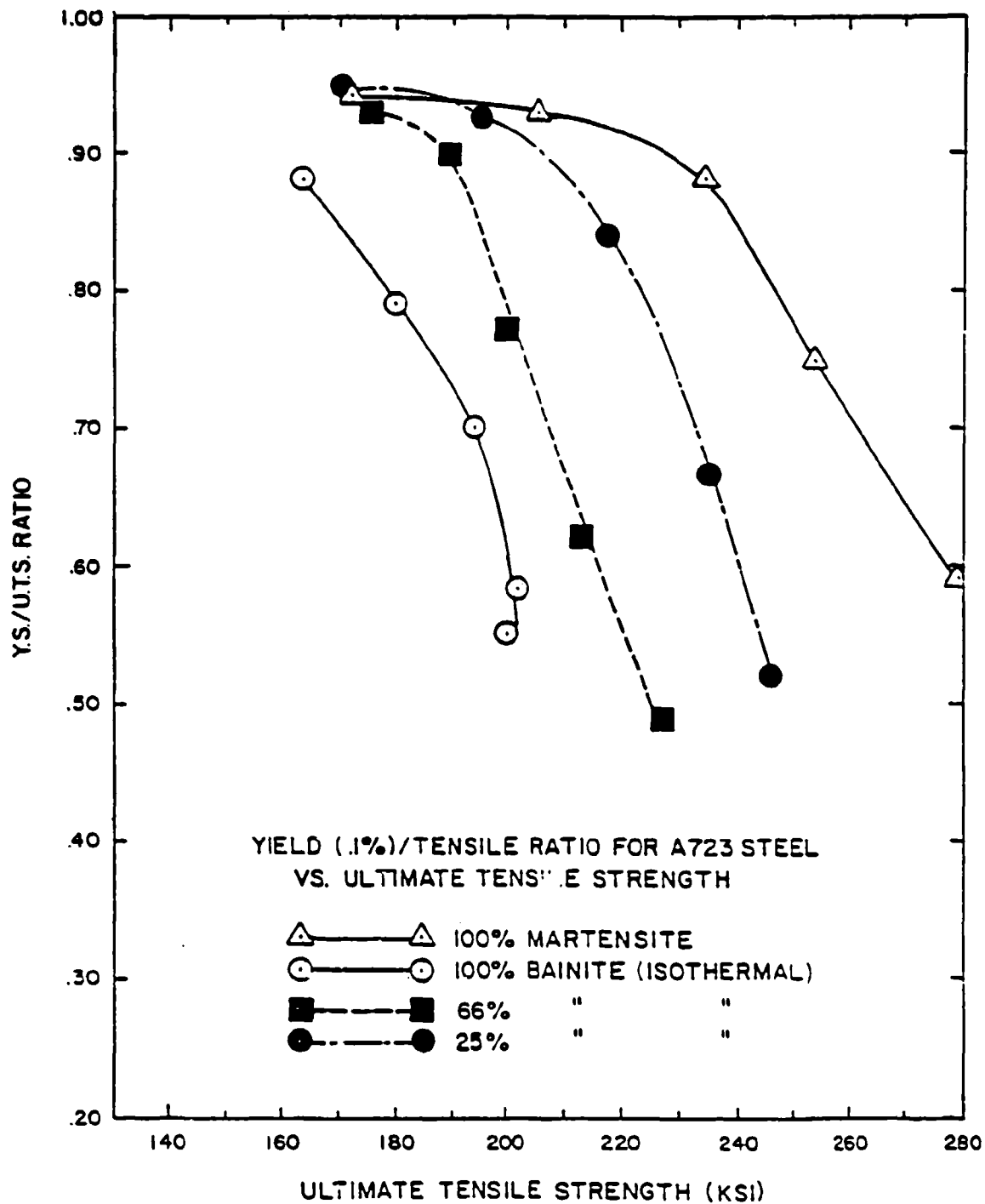
Figure 3. The effect of microstructure on the yield strength-to-ultimate tensile strength ratio as a function of tensile strength.

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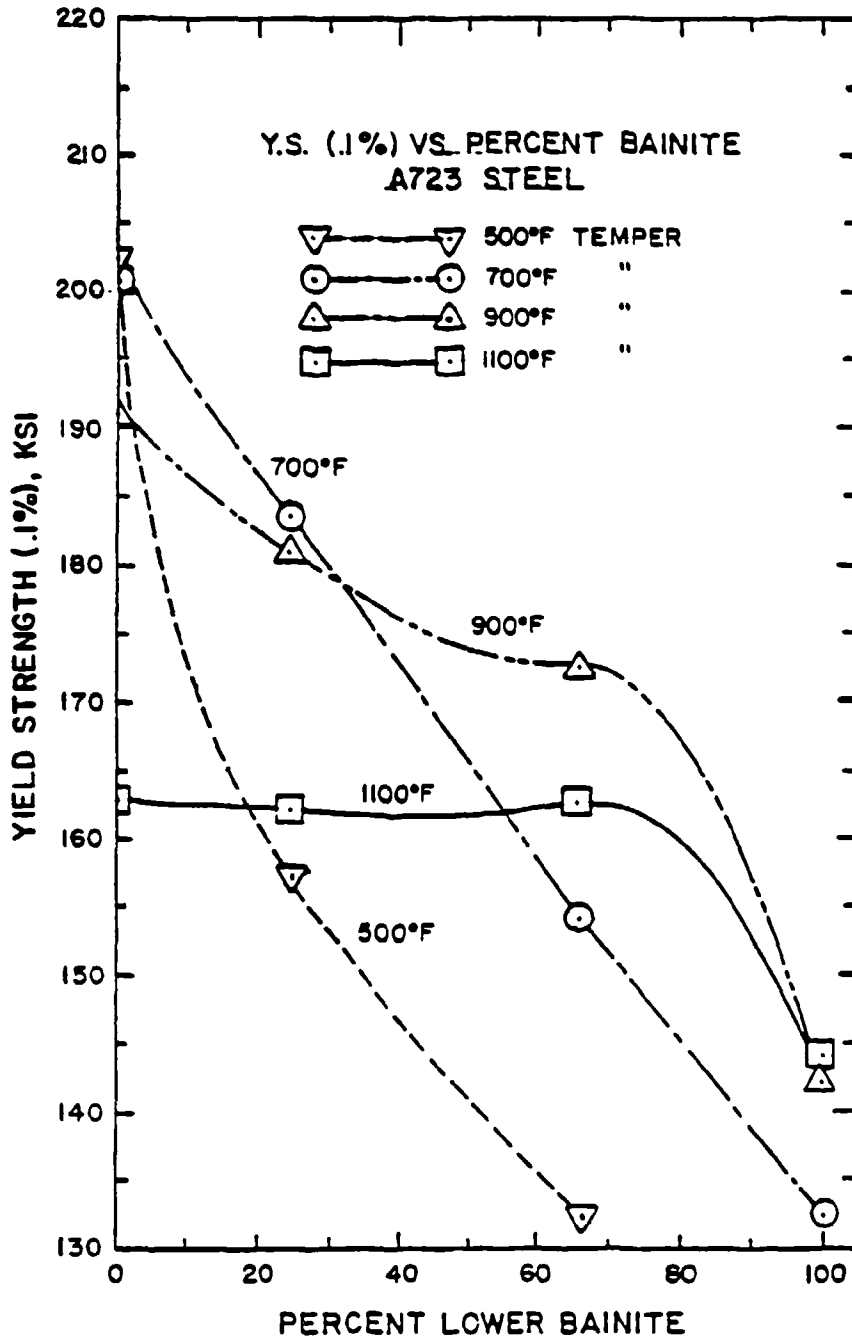
Figure 4. The effect of tempering and the percent of lower bainite on the 0.1 percent yield strength of A723 steel.

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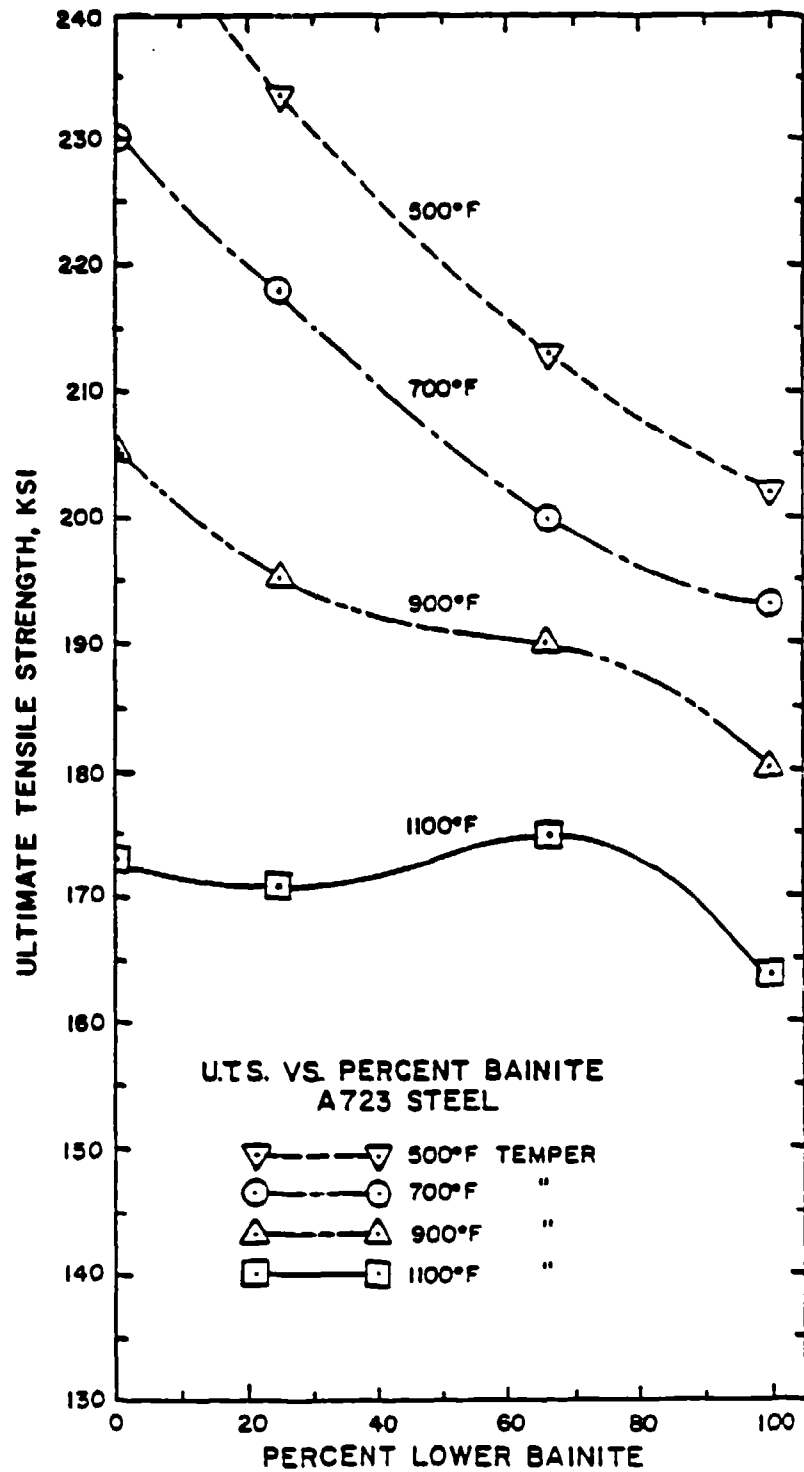
Figure 5. The effect of tempering and the percent of lower bainite on the ultimate tensile strength of A723 steel.

Temper Temp. ---

| 500°F | 700°F | 900°F | 1100°F | 1300°F |
| (260°C) | (371°C) | (482°C) | (593°C) | (704°C) |
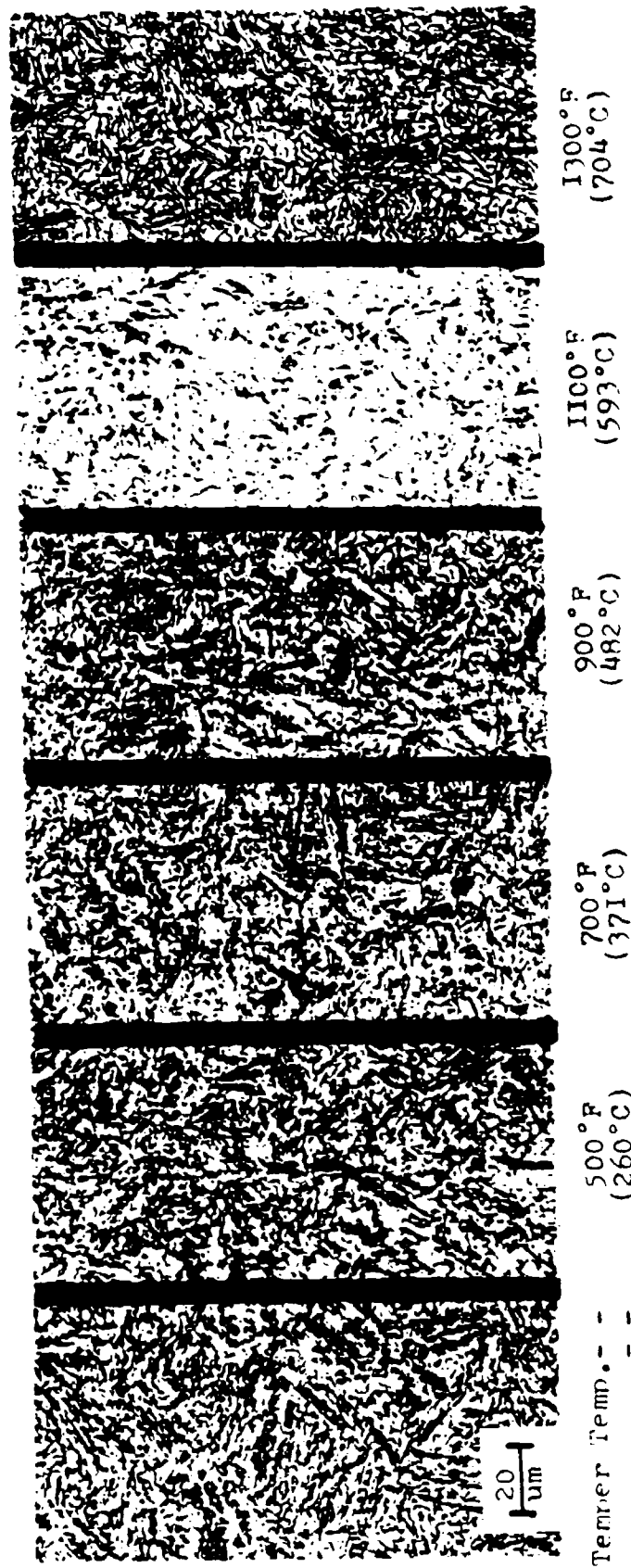
Figure 6. The effect of tempering on A723 steel with a microstructure of 66 percent lower bainite and martensite austenitized at 830°C and isothermally transformed at 250°C for 2-1/4 hours. Picral etch 2%. Magnification 1000X.

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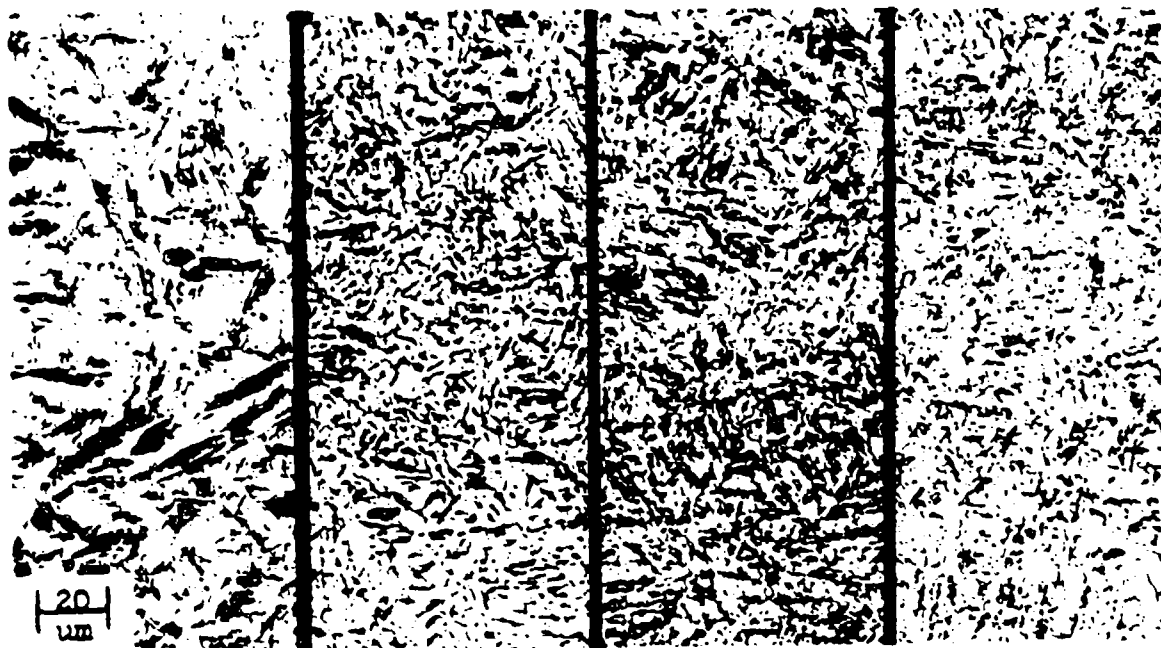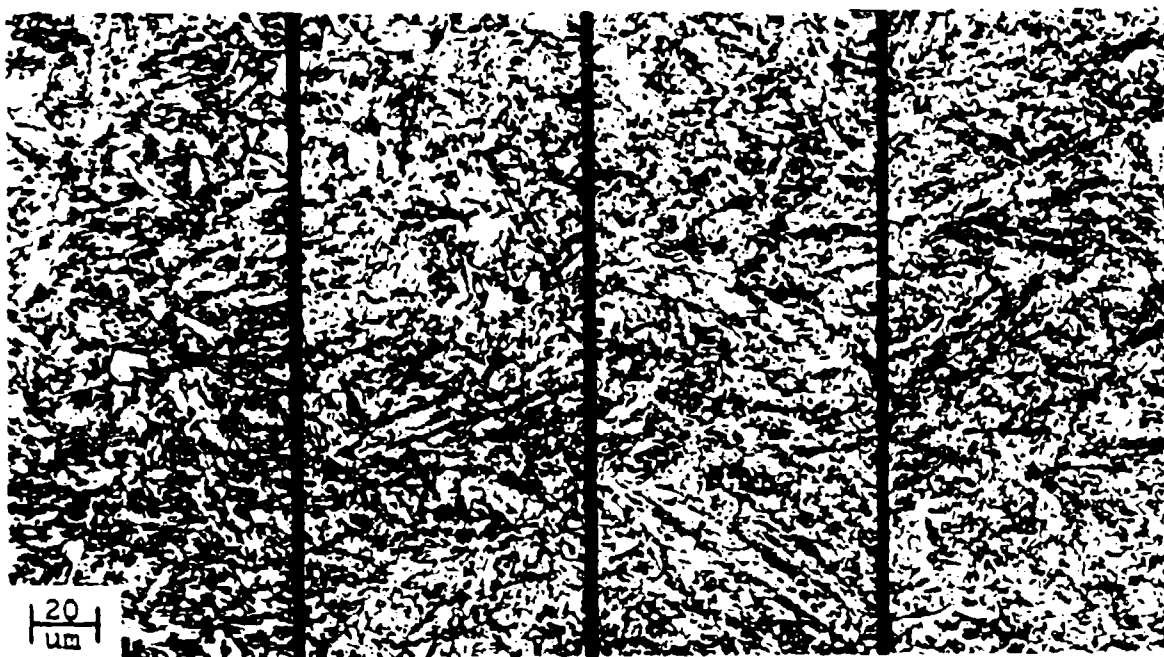
Figure 7. Etched microstructures for A723 steel consisting of martensite, bainite, and mixtures of both as follows: Untempered condition - (a) 100% martensite, (b) 25% bainite, (c) 66% bainite, (d) 100% bainite. Tempered condition at 593°C for one hour - (e), (f), (g), and (h), respectively. Picral etch 2%. Magnification 1000X.

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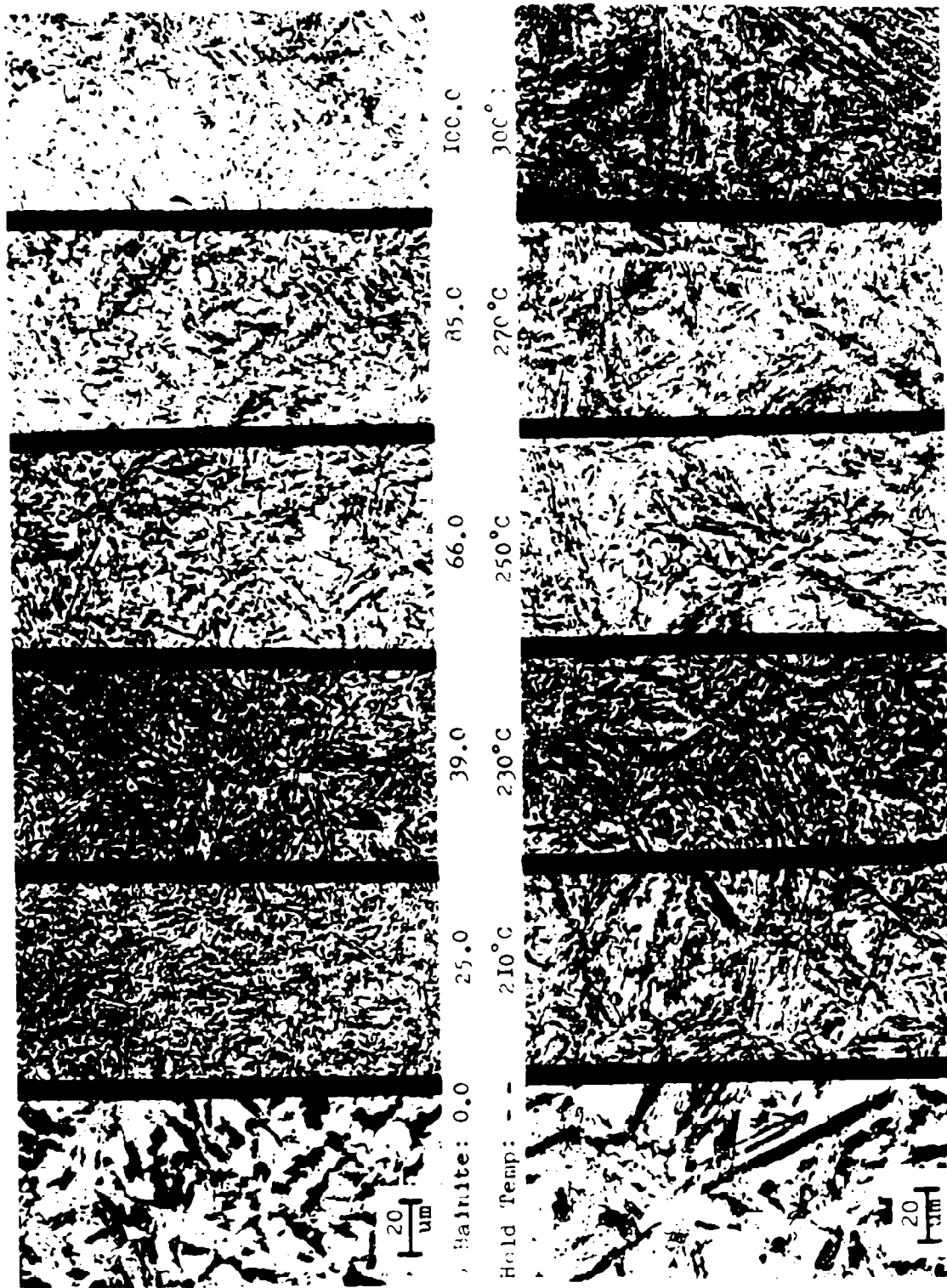
Figure 8. Mixed microstructures with increasing amounts of lower bainite developed from isothermally transformed austenite cooled from 830°C (top) and 930°C (bottom) after holding for 2-1/4 hours at isothermal transformation temperatures, no temper. Picral etch 2%. Magnification 1000X.
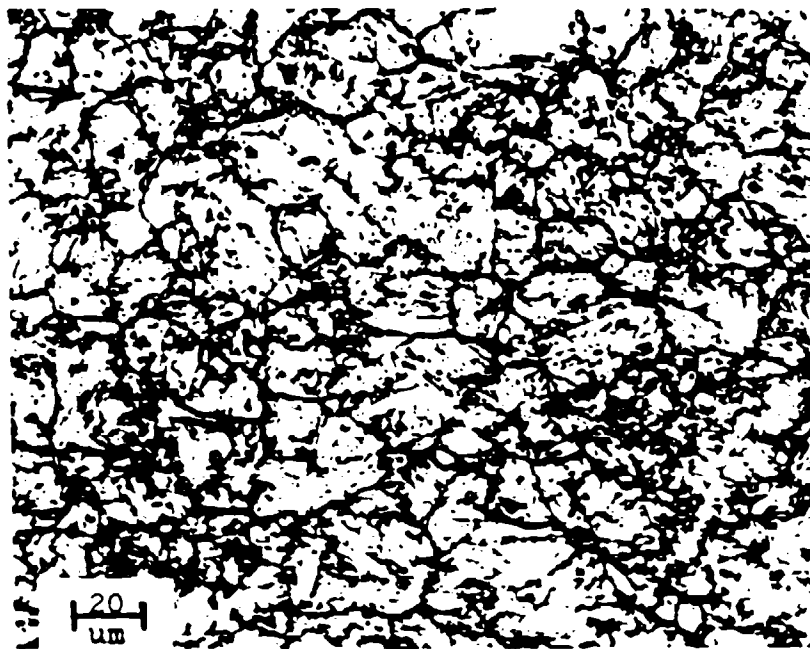
(a)

(b)

Figure 9.   Grain sizes from two austenitizing temperatures for A723 steel
            cooled to room temperature and tempered at 593°C. (a) 830°C,
            ASTM average grain size 10.5; (b) 930°C, grain size 7.3.
            Etch 1% aqueous solution of picric acid with a water softener
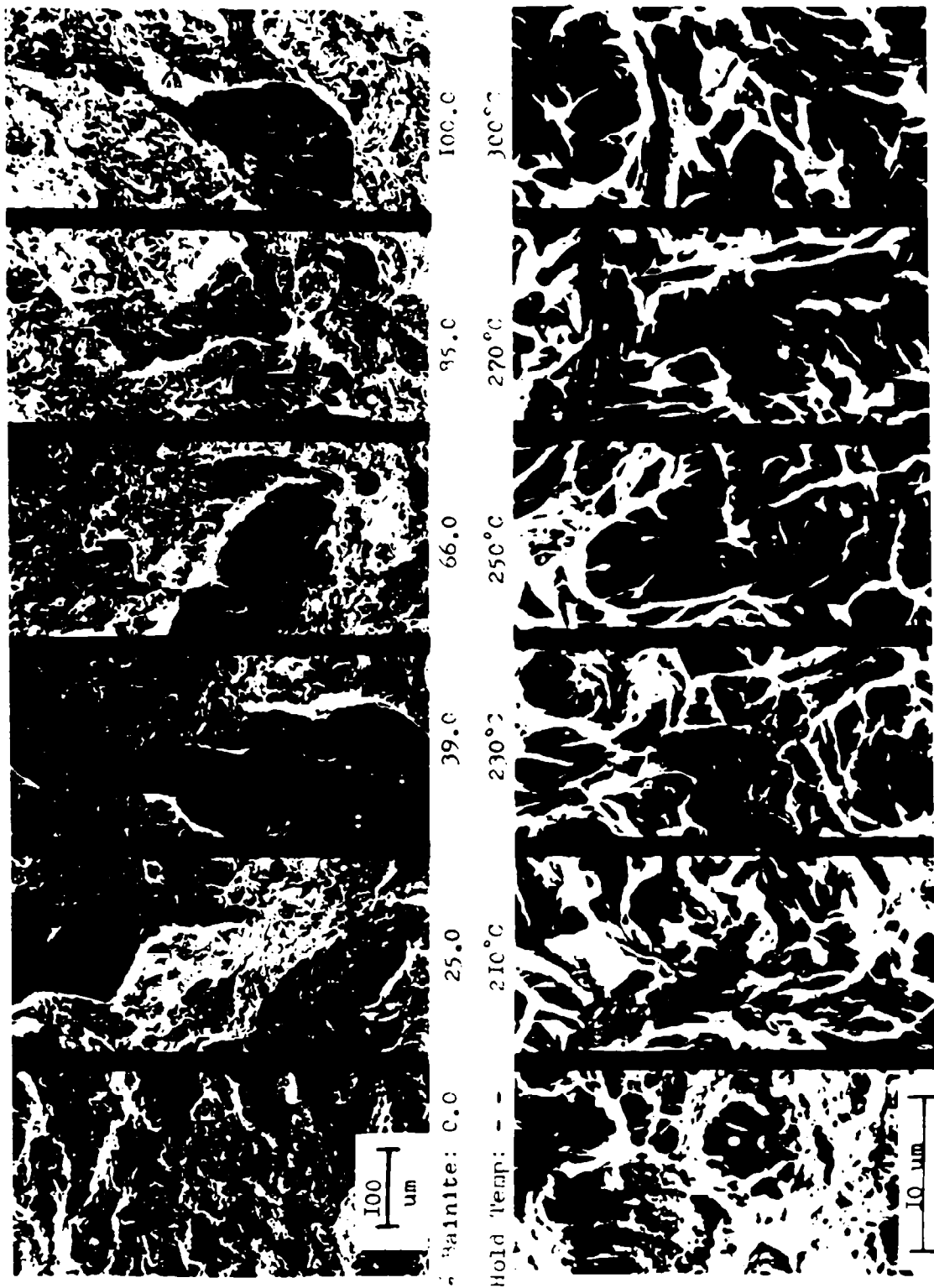   added. Magnification 1000X.
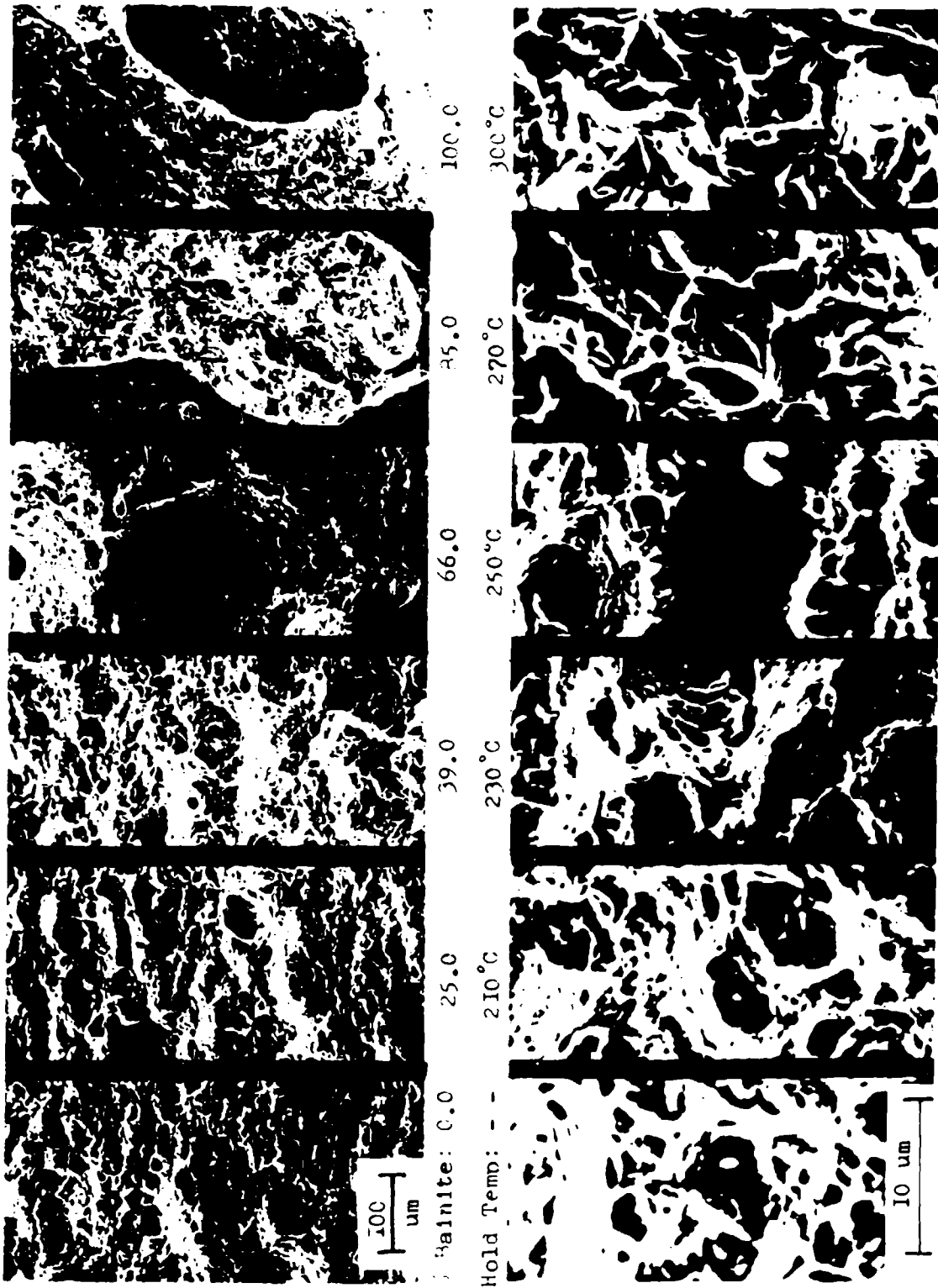
Figure 10. SEM fracture surfaces (slow-bend, -40°C) of martensite and/or bainite by isothermally transforming austenite cooled from 830°C and held for 2-1/4 hours at temperatures shown. All microstructures were tempered at 593°C for one hour. Magnification 150X, 3000X.
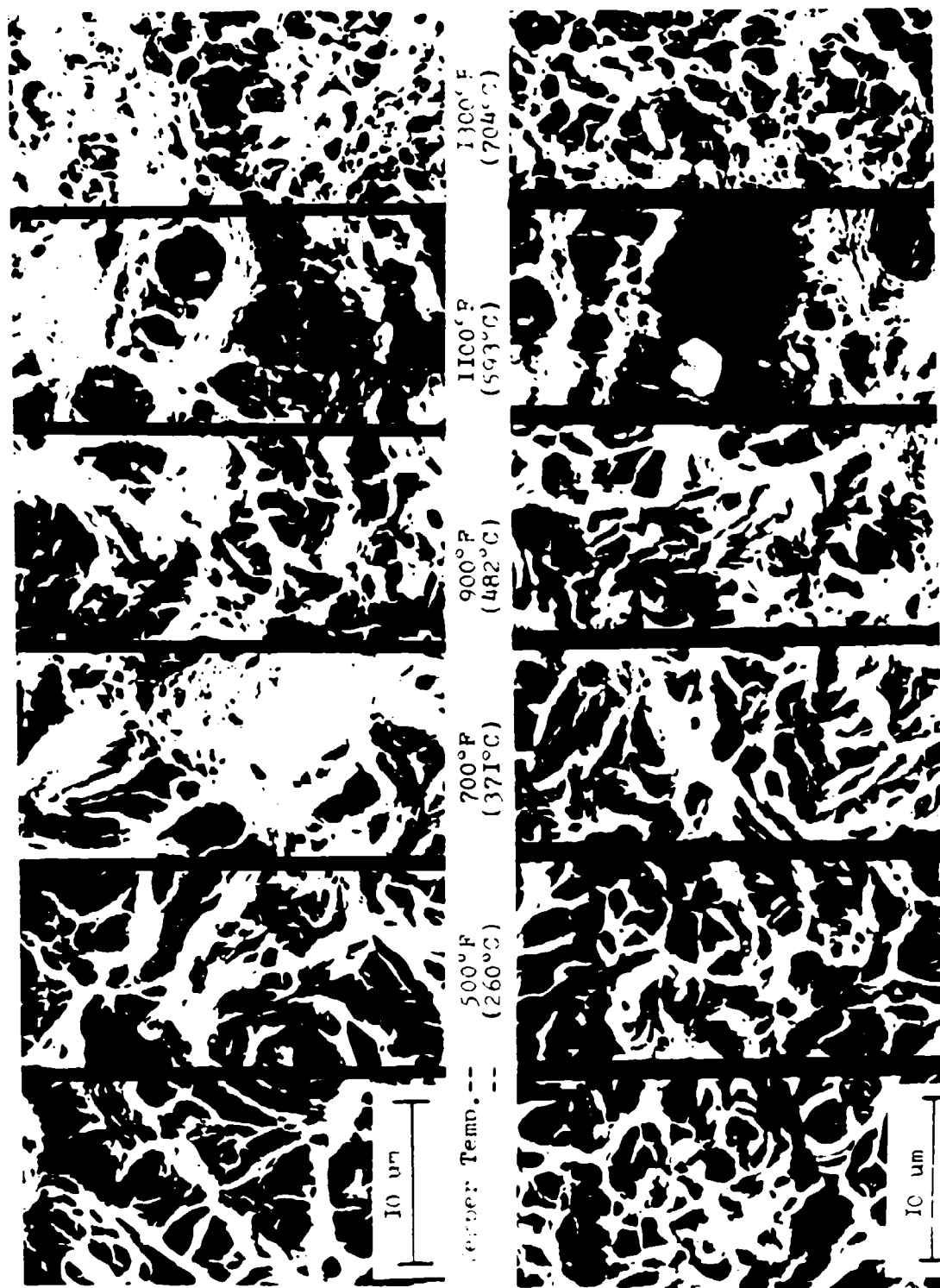
Figure 11. SEM fracture surfaces (slow-bend, -40°C) of martensite and/or bainite by isothermally transforming austenite cooled from 930°C and held for 2-1/4 hours at the temperatures shown. All structures were tempered at 593°C for one hour. Magnification 150X, 3000X.

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Figure 12. SEM showing the effect of tempering temperatures on fracture surfaces (slow-bend, -40°C) of A723 steel with mixed microstructures of lower bainite and martensite formed by austenitizing at 830°C and isothermally transformed as follows: (a) 25% bainite at 210°C for 2-1/4 hours, (b) 66% bainite at 250°C for 2-1/4 hours. Magnification 3000X.
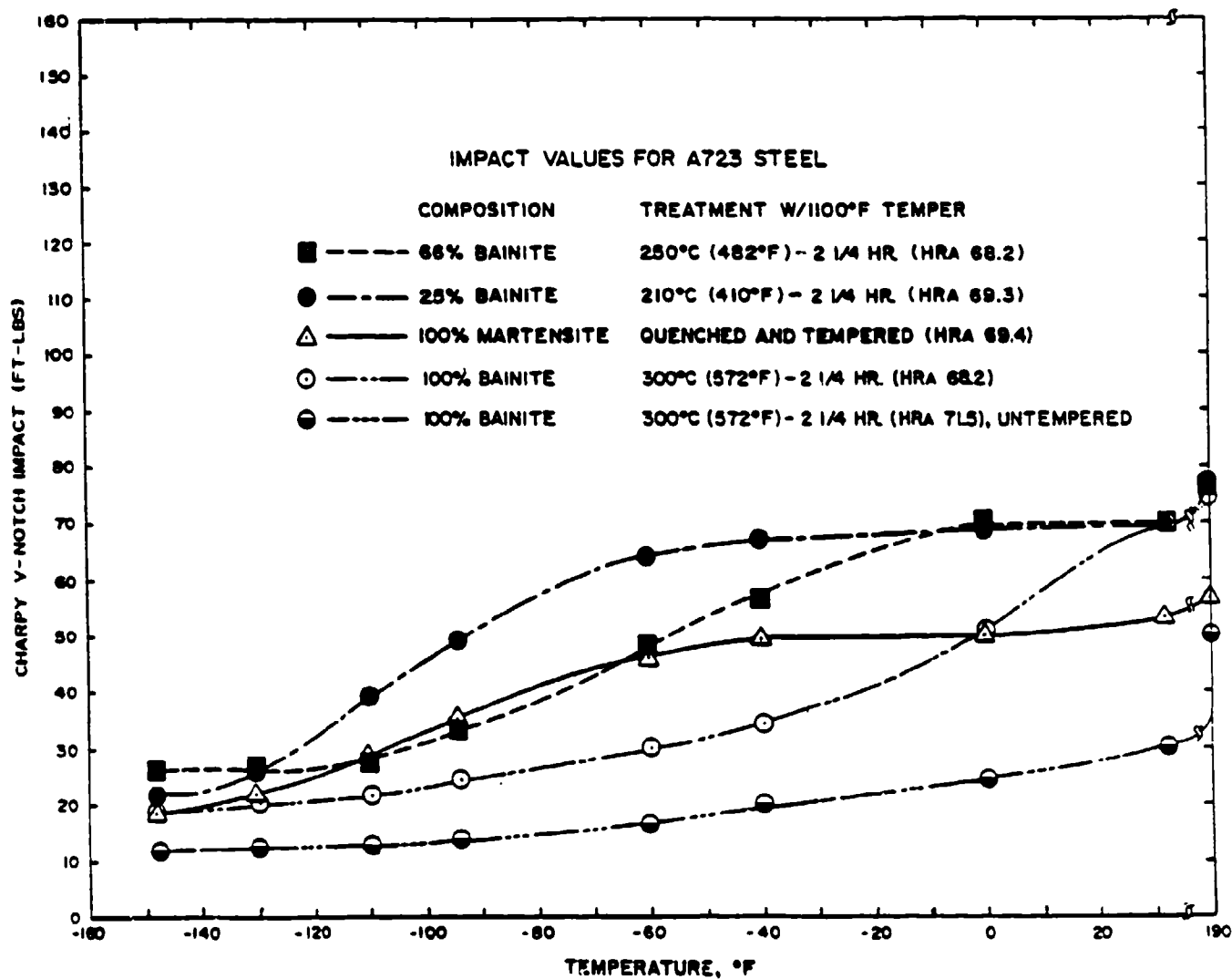
Figure 13. Charpy V-notched impact curves for martensite, mixed
microstructures, and bainite with thermal treatments
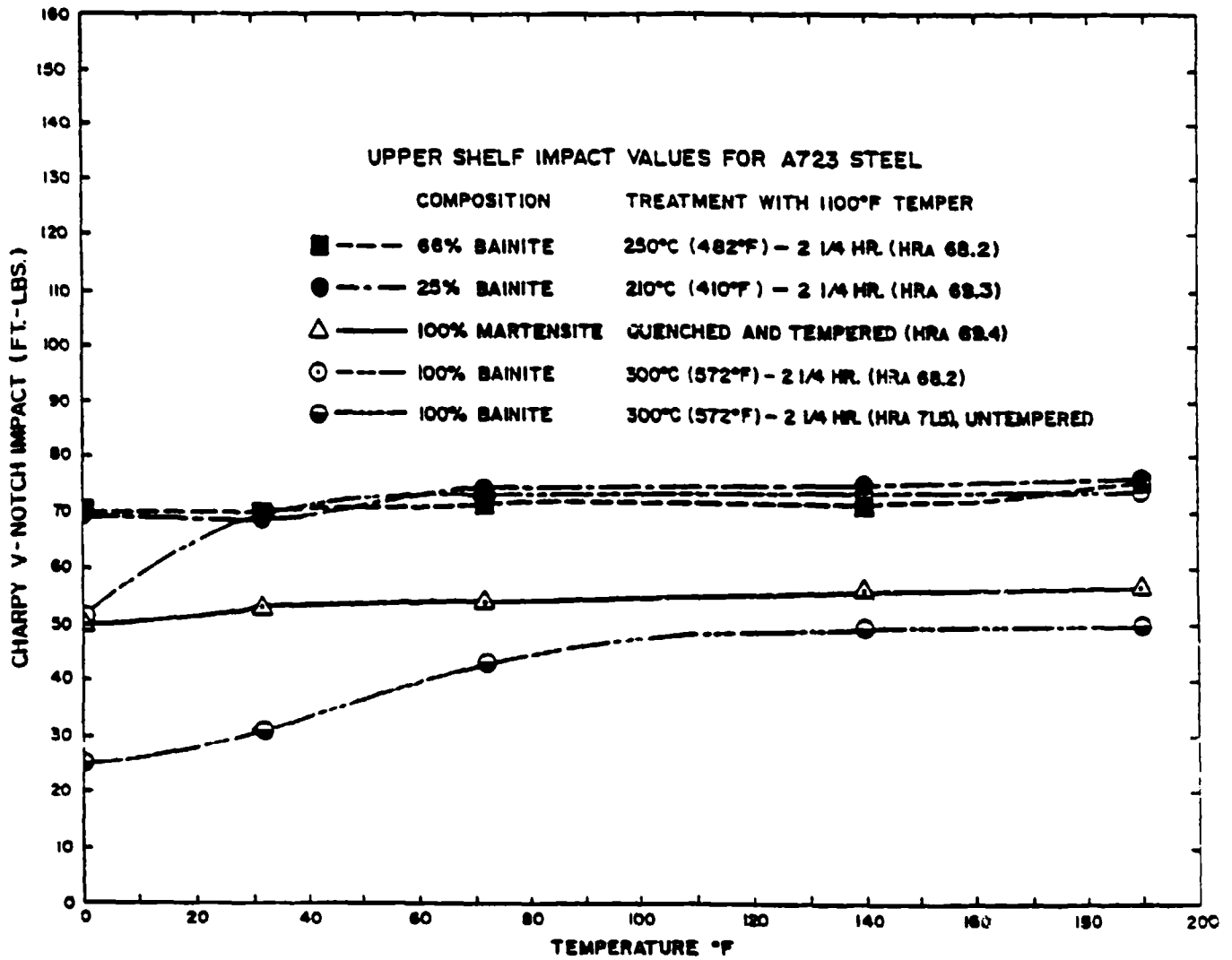shown and tested from -100° to 0°C.

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Figure 14. Upper shelf energy Charpy V-notched impact curves for
martensite, mixed microstructures, and bainite with
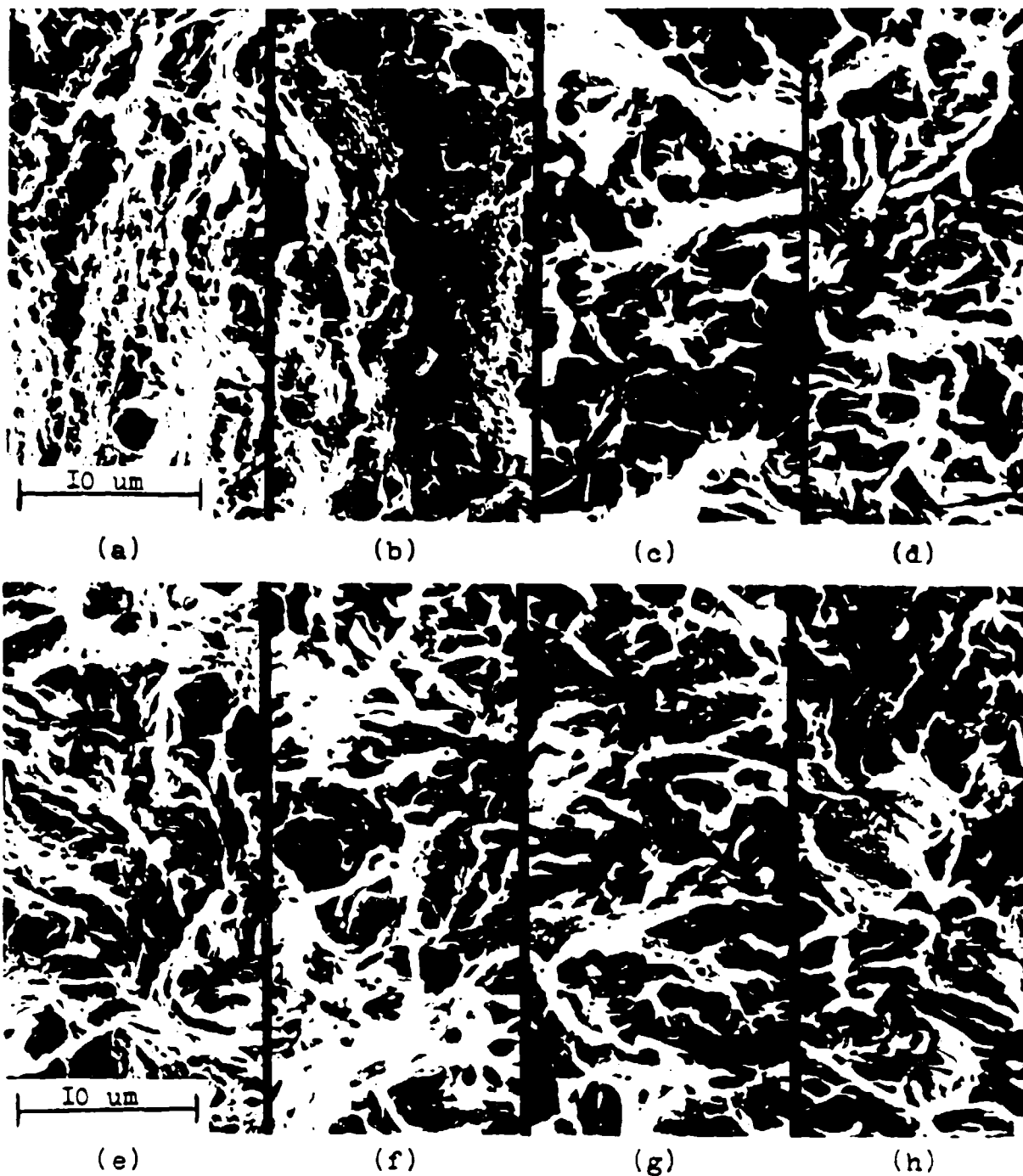thermal treatments shown and tested from -17.8° to 88°C.

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Figure 15. SEM showing impact fracture surfaces for 100% martensite, mixed microstructures with 25% and 66% bainite, and 100% bainite, respectively, as follows: (a), (b), (c), (d) tested at -40°C with impact values of 49.2, 67.3, 56.0, and 34.7 ft-lbs, respectively; (e), (f), (g), and (h) tested at -70°C with impact values of 36.3, 49.5, 33.4, and 24.5 ft-lbs, respectively. Magnification 3000X.
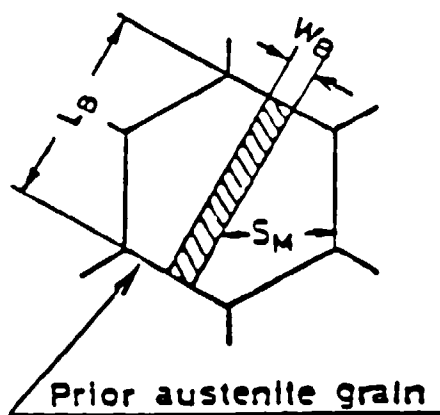
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APPENDIX

Fig. 3 — Schematic diagram of lower bainite and martensite size as shown on Table II.

Table II. Metallographic Parameters of Mixed Structure
of Martensite and Lower Bainite

V_b (Pct)	W_b (μm)	L_b (μm)	S_M (μm)
10	1.1	9.3	5.7
25	1.1	9.1	4.3
50	1.2	9.0	2.7
75	1.4	8.8	2.0

(Courtesy of The Metallurgical Society of AIME, Warrendale, PA (Ref 6))
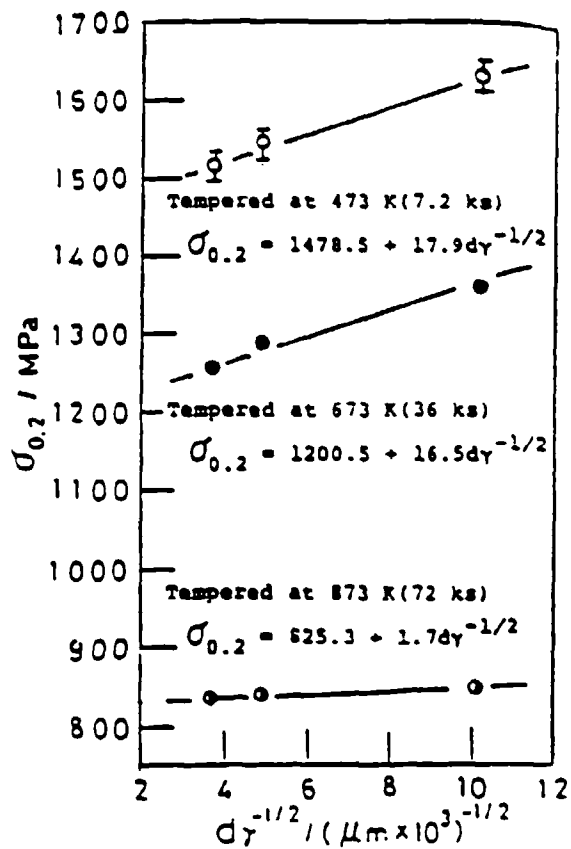
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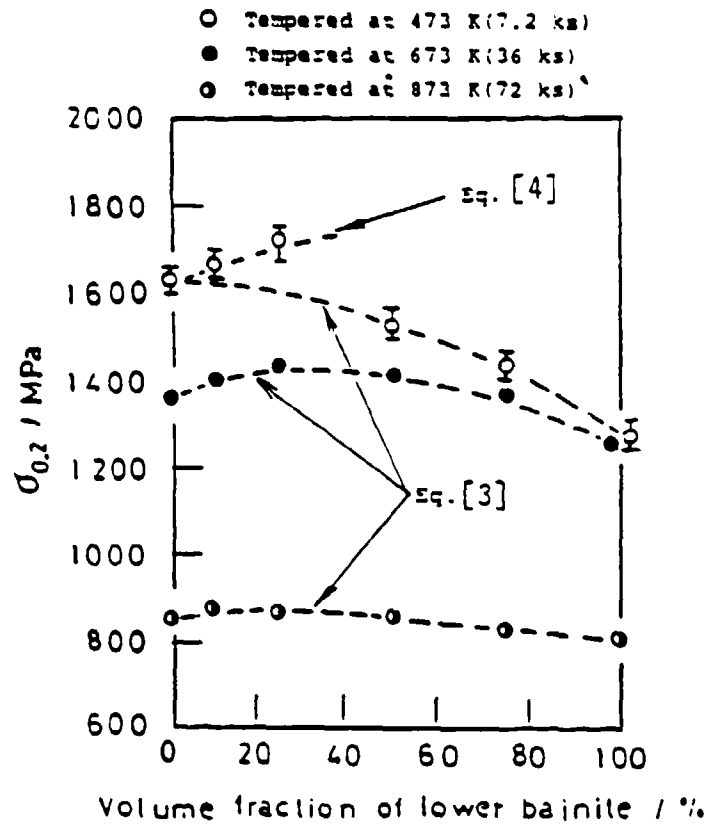Fig. 16 — dγ dependence of $\sigma_{0.2}$ in a 0.40 pct C-Ni-Cr-Mo steel.

Fig. 14 — Comparison of experimental values of $\sigma_{0.2}$ in a mixed structure of martensite and lower bainite using the calculated law of mixtures.

$$\sigma_{0.2}^{Mix} = \sigma_{0.2}^{M} \cdot (1 - V_B) + \sigma_{0.2}^{B} \cdot V_B \qquad [1]$$

$$\sigma_{0.2}^{M} = \sigma_i + kS_M^{-\tfrac{1}{2}}$$

$$\sigma_{0.2}^{Mix} = (\sigma_i + kS_M^{-1/2})(1 - V_B) + \sigma_{0.2}^{B} \cdot V_B \qquad [2]$$

Then, Eq. [2] can be rewritten in convenient form

$$\sigma_{0.2}^{Mix} = \sigma_i + kS_M^{-1/2} - (\sigma_i + kS_M^{-1/2} - \sigma_{0.2}^{B})V_B \qquad [3]$$

$$\sigma_{0.2}^{Mix} = \sigma_i + kS_M^{-1/2} \qquad [4]$$

(Courtesy of The Metallurgical Society of AIME, Warrendale, PA (Ref 8))

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